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Corrosion Rate, Effect of Soil Properties

Development of a Sensor System to Calculate Corrosion Rates

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Technical Update, December 2013

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ABSTRACT

This report addresses corrosion of substation ground grids and the development of a corrosion sensor system and supporting algorithms that can be used in the field to quickly estimate the corrosion rate of a metal in soils of low resistivity.

The system is based on the linear polarization resistance (LPR) technique, an electrochemical method of calculating corrosion rates by measuring the relationship between electrochemical potential and the electric current between electrodes. Quantifying the corrosion rate at a particular site is essential to understanding the progression of corrosion over time.

The sensor system will dynamically measure ground grid corrosion using probes that transmit data via cellular uplinks to a base station where the data will be compiled and made available for analysis. Once fully developed and deployed, the sensor system would enable substation operators to assess the condition of ground grids, discriminate between different types of corrosion, and develop cost-effective corrosion mitigation strategies to protect substation equipment, ensure public safety, and maintain service reliability.

Ultimately, the technology and methodologies developed in this project will support fleet management of aging ground grids. A fleet management approach would enable substation operators to assess the condition of a population of ground grids based on the electrical and environmental conditions that influence corrosion and predict future corrosion progression and associated risk. With this knowledge and supporting analytical tools, substation operators would be able to make informed, risk-based asset management decisions regarding ground grids and optimize maintenance budgets. Looking forward, this approach will be applied not only to ground grids but also to other substation and transmission line components.

The report summarizes EPRI research and development performed through 2012 on ground grid corrosion mechanisms and impacts, sensor technologies, algorithms, and environmental data modeling, as well as R&D continuing in 2013 and beyond.

Keywords
Substations
Ground grids
Corrosion

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CHALLENGES FACING SUBSTATION GROUND GRIDS

Introduction

This report addresses corrosion of substation ground grids and the development of a corrosion sensor system and supporting algorithms that can be used in the field to quickly estimate the corrosion rate of a metal in soils of low resistivity.

The system is based on the linear polarization resistance (LPR) technique, which has been used in laboratory settings for many years but had not been adapted for field use prior to the development effort described in this report. LPR is an electrochemical method of calculating corrosion rates by measuring the relationship between electrochemical potential and the electric current between electrodes. Quantifying the corrosion rate at a particular site is essential to understanding the progression of corrosion grids over time.

The sensor system will dynamically measure ground grid corrosion via linear polarization resistance probes. Probe data will be transmitted via cellular uplinks to a base station where the data will be compiled and made available for analysis. Once fully developed and deployed, this sensor system would enable substation operators to assess the condition of ground grids, discriminate between different types of corrosion, and develop cost-effective corrosion mitigation strategies to protect substation equipment, ensure public safety, and maintain service reliability.

Ultimately, the technology and methodologies developed in this project will support fleet management of aging ground grids. A fleet management approach would enable substation operators to assess the condition of a population of ground grids based on the electrical and environmental conditions that influence corrosion, and predict future corrosion progression and associated risk. With this knowledge and supporting analytical tools, substation operators would be able to make informed, risk-based asset management decisions regarding ground grids and optimize maintenance budgets. Looking forward, this approach will be applied not only to ground grids but also to other substation and transmission line components.

The report summarizes EPRI research and development performed through 2012 on ground grid corrosion mechanisms and impacts, sensor technologies, algorithms, and environmental data modeling, as well as R&D continuing in 2013 and beyond.

Report Organization

Chapter 1 provides an introduction and overview of substation ground grid challenges, with a focus on corrosion.

Chapter 2 presents a discussion of corrosion fundamentals, including mechanisms of corrosion, environmental factors, and impacts on substation ground grids.

Chapter 3 summarizes EPRI R&D performed to date regarding ground grid corrosion and the development of a corrosion sensor array and data acquisition system.

Chapter 4 describes work to be performed in 2013 and beyond in developing a field-deployable ground grid corrosion sensing and data acquisition system.

Ground Grid Challenges

Substation ground grids are essential components that

- Serve as a safety feature for personnel who may be in the substation during a fault
- Minimize hazards to the public, such as step-and-touch voltages near the substation
- Provide adequate grounding for substation equipment—especially control room electronics

Many substations were designed and installed 50 or more years ago. Corrosion of aging ground grids is one of the key factors (along with increased power flows, physical damage, and copper theft) contributing to potential degradation and decreased effectiveness in performing essential safety and protection functions.

Substation ground grids are usually made of copper conductors placed below grade and joined together and to above-grade structures with various types of connectors. Some connections are between like metals (for example, copper to copper), while others must provide durable low-resistance connections between dissimilar metals (for example, copper to steel). While above-grade connections are visible and can be inspected with relative ease, below-grade connections are not visible and are not readily accessible for inspection or testing.

A 2008 EPRI report (1013910) presented the results of a utility survey of methods used for ground grid integrity assessment. Results showed that some utilities perform condition assessment of ground grids, while many do not. Several utilities have reported degradation of the substation ground grid and/or connections between grid elements and/or connections to substation structures.

In response to this recognized problem, EPRI developed a research plan to study corrosion of substation ground grids and connections and to quantify grounding grid corrosion. The development of a sensor array based on LPR technology is a primary objective of the overall research plan.

The expected outcome of this research includes estimates of corrosion likelihood and rates in various types of environments and recommendations for corrosion mitigation strategies that could be applied to substation ground grids and connections. Ultimately, the tools and methodologies developed in this project will support a holistic approach to fleet management of aging substation ground grids.

Corrosion in Ground Grids

Stressors that contribute to corrosion include electrical effects from faults or lightning and environmental effects including soil acidity, moisture, and temperature. Metal dissimilarities can also accelerate the corrosion process.

As a result of these different stresses, several types of corrosion affect substation ground grids and other components. These include:

- General corrosion (uniform)
- Pitting/crevice corrosion (localized)
- Galvanic
- Concentration cell (differential oxygen or moisture)
- Metal ion cell
- Fatigue
- Microbial
- Long line effects
- Stray current (AC or DC)

The LPR sensor technology can discriminate between general and stray current corrosion. Further development will enable discrimination between other corrosion types. This work involves characterization and modeling of soil types from multiple substation locations, as well as gathering and analyzing environmental data. The soil and environmental data supports the development of algorithms that will process the sensor measurements and environmental conditions to calculate site-specific corrosion rates.

Quantifying corrosion rates at specific substations is a key objective of the project. Traditionally, utilities estimated corrosion rates by periodically measuring corrosion pitting on metal surfaces. This approach provides a crude estimation of corrosion rate and does not discriminate between the types of corrosion. The LPR technique accurately measures corrosion rate and, coupled with extensive soil and historical environmental data, enables accurate projections of component aging due to corrosion degradation. This capability would support informed asset management decision making regarding component repair/replacement and corrosion mitigation strategies.

2
CORROSION FUNDAMENTALS

This chapter presents an overview of corrosion mechanisms that affect substation ground grids. The following material is adapted from the EPRI technical updates *Evaluation of New and Emerging Corrosion Sensors: Corrosion Model Development for Soils* (EPRI report 1024123) and *Corrosion Probe Development: Interim Report* (1024121).

Corrosion Basics

Common metals are found in nature as chemical compounds such as oxides, chlorides, or sulfides. They seldom occur as pure metals. After they have been refined to an almost pure metal by man, nature wants to change them back to their original state in a process known as corrosion.

Corrosion is defined as the degradation of metals by chemical or electro-chemical reaction with the environment. The fundamental reaction involves a transfer of electrons through the metallic path of the structure. In a moist or wet environment, some atoms become positively charged ions or cations by losing electrons; and some become negatively charged ions or anions. As the charged ions migrate towards their respective pole, a portion of the metal surface goes into solution and corrosion occurs. The entire process may be divided into an anodic reaction (oxidation) and a cathodic reaction (reduction). The anodic reaction represents loss of charges by the corroding metal, and the cathodic reaction represents a gain of charges. The flow of electricity between the anodic and cathodic areas may be generated by local cells set up either on a single metallic surface or between dissimilar metals. Figure 2-1 illustrates the process and shows how mitigation of the corrosion may be achieved by altering the characteristics of any one of the four components required for electrochemical corrosion to occur.

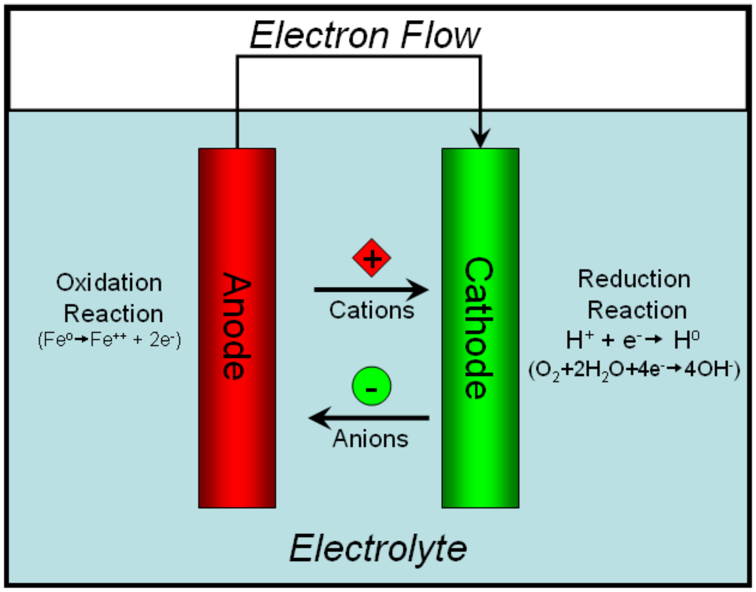


Figure 2-1
The four components required for electrochemical corrosion to occur

A corrosion cell consists of two electrically conductive structures or sites connected by an ionically conductive electrolyte (soil or water). As an electrical current passes, it must change from an electronic current to ionic current and back to electronic current. These changes of conduction mode are always accompanied by oxidation/reduction reactions.

Research has shown that while the oxidation-reduction reactions occur simultaneously, they can be located within a pit field or some distance down the right of way (ROW). In every case there is always some measurable distance between the two reactions.

In a chemical reaction, the hydrogen is oxidized by oxygen contained within water; and the electrons pass directly from the hydrogen to the oxygen. In the electrochemical reaction in a galvanic cell, the hydrogen is oxidized at the anode by transferring electrons to the anode; and the oxygen is reduced at the cathode by accepting electrons from the cathode. The ions produced in the electrode reactions, in this case positive hydrogen ions and the negative hydroxyl (OH-) ions, will recombine in the solution to form the final product of the reaction: water. The movement of the hydrogen and hydroxyl ions through the electrolyte constitute the ionic current flow.

Electromotive Series (driving force)

The tendency for metals to corrode by hydrogen ion displacement is indicated by their position in an electromotive series like the one shown in Table 2-1. The voltages listed in this table are for metals in contact with a solution in which the activity of the ion indicated is one mole per 1,000 grams of water and the temperature is 77°F (25°C). Different voltages will be obtained in other solutions. Refer to MIL-STD-889 (Military Standard: Dissimilar Metals) for a more complete listing of the galvanic series.

Table 2-1
Electromotive series

(Anodic End)

Metal	Ion	Volts
Magnesium	Mg + 2e*	-2.34
Aluminum	Al + 3e	-1.67
Zinc	Zn + 2e	-0.76
Chromium	Cr + 3e	-0.71
Iron	Fe + 2e	-0.44
Cadmium	Cd + 2e	-0.40
Nickel	Ni + 2e	-0.25
Tin	Sn + 2e	-0.14
Lead	Pb + 2e	-0.13
Hydrogen	H + e	Arbitrary 0.00
Copper	Cu + 2e	+0.34

(Cathodic End)

Metals above hydrogen displace hydrogen more readily than do those below hydrogen in this series. A decrease in hydrogen ion concentration (acidity) tends to move hydrogen up relative to other metals. An increase in the metal ion concentration tends to move the metals down relative to hydrogen, although in specific cases, whether or not hydrogen evolution will occur is determined by several other factors besides the concentration of hydrogen and metallic ions.

Table 2-2 indicates consumption rates when one (1) ampere of direct current leaves a structure during the period of a year. This information is helpful when understanding the degradation rates of counterpoise, ground rods, grounding grids, and structures.

Table 2-2
Electrochemical equivalents (consumption rates)

Metal	**Pounds Removed per Amp per Year**
Carbon (C++++)	2.16
Carbon (C ++)	4.23
Aluminum	6.47
Magnesium	8.76
Chromium	12.5
Iron	20.1
Nickel	21.1
Cobalt	21.2
Copper (Cu++)	22.8
Zinc	23.5
Cadmium	40.5
Tin	42.7
Copper (Cu +)	45.7
Lead	74.2

Mechanisms of Corrosion (Half Reactions)

Corrosion involves chemical reactions that occur at both the cathodic and anodic sites. To understand these reactions, it is easier to examine each site individually. At the anode:

$$M \Rightarrow M^{n+} + e^{n-} \qquad \text{(anodic site reaction)}$$

Where:

M = metal involved

n = valence of the corroding metal

e = electrons

The metal at the anodic site dissolves or transforms into a metal ion in solution. Electrons that are lost (oxidized) in the half reaction migrate through the structure to the cathodic site for the reduction reaction to occur. At the cathode:

$R^+ + e^- \Rightarrow R^0$ (cathodic site reaction)

Where:

R^+ = positive ion in solution

e^- = electron

R^0 = reduced atom

The reduced atom can be released as a gas or deposited on the cathodic site resulting in passification of the metal surface. Passification stabilizes the surface and protects it from corrosion as long as the hydrogen atoms are left undisturbed.

In alkaline and neutral aerated soil (electrolyte), the predominant cathodic reaction is:

$O_2 + 2H_2O + 4e^- \Rightarrow 4(OH)$

In aerated acidic conditions, the cathodic reaction is generally:

$O_2 + 4H^+ + 4e^- \Rightarrow 2H_2O$

These are all examples of basic chemical reactions that involve the gain of electrons in a reduction process. Another example of a half reaction and a combined reaction would be the following:

Copper:

$Cu^o \longrightarrow Cu^{++} + 2e^-$

Having lost two electrons, the detached positive copper ions bear two positive charges. The released electrons travel through the metal or other conducting media to the cathode area. The electrons reaching the surface of the cathode through the metal meet and neutralize some positively charged ions (such as hydrogen) that have arrived at the same surface through the electrolyte. In losing their charge, these positive ions become neutral atoms again and may combine to form a gas.

$2H^+ + 2e^- \longrightarrow H_2$

The removal of hydrogen ions from water in the electrolyte results in the accumulation of OH^- ions and thus increases the alkalinity at the cathode making the solution less acidic. Other common reactions occurring at the cathode are shown below.

The occurrence of particular reactions depends on such factors as pH and type of electrolyte.

$4H^+ + O_2 + 4e^- \longrightarrow 2H_2O$

$O_2 + 2H_2O + 2e^- \longrightarrow H_2O_2 + 2OH^-$

$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$

Steel (iron):

$Fe \Rightarrow Fe^{++} + 2e^{-}$ (anodic reaction)

$O_2 + 2H_2O + 4e^{-} \Rightarrow 4(OH)$ (cathodic reaction)

Combining the cathodic and anodic reactions we see:

$2Fe + O_2 + 2H_2O \Rightarrow 2\ Fe^{++} + 4(OH^{-})$

Ferrous ions generally oxidize to ferric ions (Fe^{+++}), and these ions then combine with hydroxide ions (OH) formed at the cathode to give a corrosion product called rust ($FeOOH$ or $Fe_2O_3 + H_2O$).

Zinc (Galvanizing):

$2Zn + O_2 \Rightarrow 2ZnO$

(Combining zinc and oxygen results in the formation of zinc oxide.)

$ZnO + H_2O \Rightarrow Zn(OH)_2$

(Combining zinc oxide and water results in the formation of zinc hydroxide.)

$CO_2 + H_2O \Rightarrow H_2CO_3$

(Combining carbon dioxide and water results in the formation of carbonic acid.)

$Zn(OH)_2 + H_2CO_3 \Rightarrow ZnCO_3 + 2H_2O$

(Combining zinc hydroxide and carbonic acid results in zinc carbonate and water.)

$ZnCO_3 + Zn(OH)_2 \Rightarrow \square ZnCO_3) + ZnO + H_2O$

(Zinc carbonate and zinc hydroxide results in zinc carbonate hydroxide.)

Or

$ZnCO_3 + H_2O \Rightarrow (ZnCO_3) * (H_2O)$

(Zinc Carbonate and water hydrate results in hydrated zinc carbonate.)

Environmental Factors

Five factors are considered to significantly influence corrosion rates in soil environments. These factors are hydrogen ion concentration (pH), soil resistivity, moisture, soil classification, and temperature. The research conducted in this project confirms that each factor does contribute to corrosion rates and provides a weighting factor that may guide the selection of sensor arrays to trend or monitor system degradation.

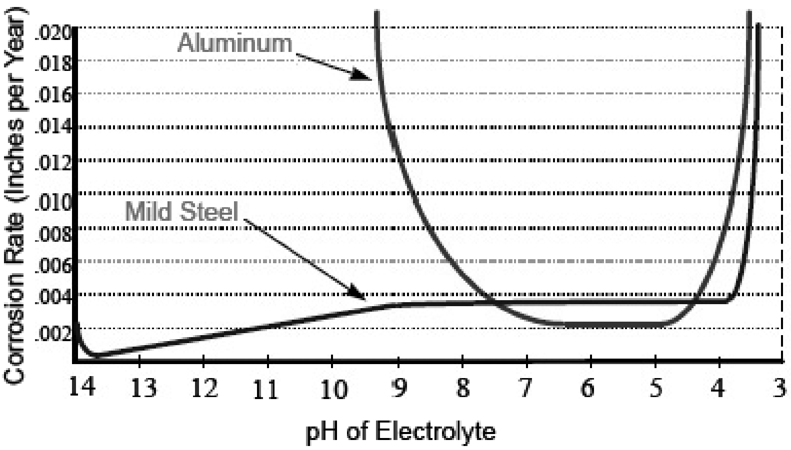
Hydrogen Ion Concentration (pH)

The hydrogen ion concentration of the soil or water in which a structure is located can affect the corrosiveness of the environment and the current required for cathodic protection. The hydrogen ion concentration is expressed in terms of pH. Stated mathematically, the pH value is the logarithm of the reciprocal of the hydrogen ion concentration. A change of one in pH value is equivalent to a change of ten times in concentration. pH values range from 0 to 14, with 0 to 7 being acidic, 7 being neutral, and 7 to 14 being alkaline.

pH readings may be taken with a meter in the field or on a separate soil sample. Most soils are slightly acidic and range from about 5.5 to about 6.5 in pH. More acidic soils, particularly those with a pH below 4, are highly conducive to corrosion activity. While localized pitting occurs quite often within soils that are relatively neutral, acidic soils will support more widespread or generalized corrosion.

Chemical corrosion is damage that can be attributed entirely to chemical attack without the additional effect of electron transfer. This type of corrosion often affects amphoteric materials such as zinc, tin, lead, aluminum, and beryllium that are sensitive to exposure to either extremely acidic or alkaline solutions. Aluminum, for example, corrodes under both low and high pH conditions as shown in Figure 2-2. Amphoteric metals should only be used within a limited pH range due their sensitivity to chemical corrosion.

Figure 2-2
Effects of pH on ferrous metal vs. an amphoteric metal[1]



Examples of corrosive solutions that can promote chemical corrosion include incompletely cured concrete, acetic acid from volatilized wood or jute, waste products from industrial plants, and water with a large amount of dissolved oxygen. Other compounds known to increase copper dissolution include pesticides, herbicides, fertilizers, and air borne pollution.

Soil Resistivity

Soil consists of a mix of gravel, silt, loam, sand, water, and dissolved salts. Electrical current flows through the earth primarily as ion movement, and this ionic conduction is heavily influenced by the concentration and kinds of salts in the soil moisture. Ionic disassociation occurs when salts are dissolved, and it is the movement of these ions under the influence of electrical potential that enables the medium to conduct electricity.

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[1] Operations and Maintenance: Cathodic Protection Systems, U. S. Department of Defense, UFC 3-570-06, 2003

Soil resistivity is the single most important characteristic used in the design of cathodic protection systems for buried structures. Protective current requirements, sacrificial anode outputs, and impressed current anode bed resistance are all dependent upon soil resistivity.

Soil corrosiveness is often classified on the basis of its resistivity, as shown in Table 2-3. In general, when soils have resistivity greater than approximately 50,000 Ωcm, corrosion is negligible and cathodic protection may not be needed.

Table 2-3
Corrosion Classification of Soil and Water

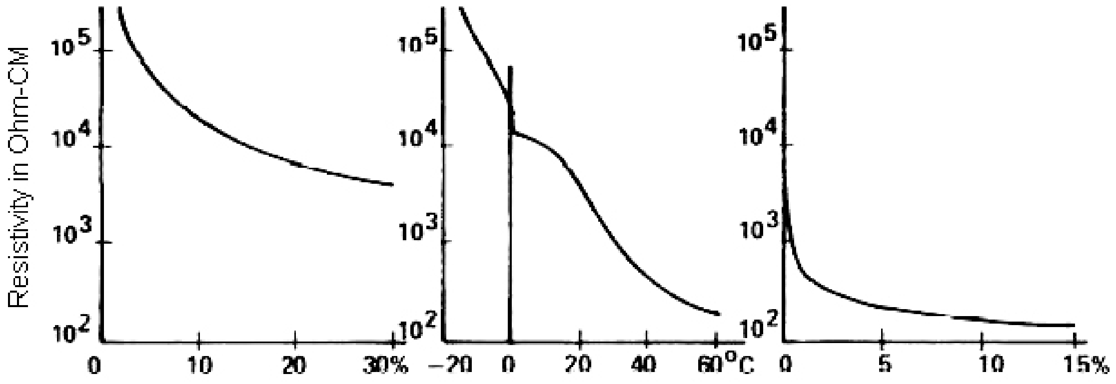
Resistivity (Ω cm)	**Corrosion Classification**
0-1000	Extremely corrosive
1000-2000	Very corrosive
2000-10,000	Corrosive
Greater than 10,000	Progressively less corrosive

Moisture Gradients

Oxygen and water content are significant contributors in sub-grade corrosion. Soil moisture is usually measured with a dielectric capacitance-type meter and is expressed as a percentage of available pore volume. Alternately, soil moisture may be directly measured in the laboratory by drying and using gravimetric techniques. Research over the years has shown that corrosion rate levels are the highest between 15% and 40% moisture content by volume and drop off outside of this range. Water tables produce a moisture gradient that can change seasonally and plate the structure with dissolved salts causing aggressive corrosion rates to occur.

Chemical Compounds:

Chlorides, sulfates, nitrates, and many other chemical compounds act as a depolarizer causing protective passivation films to break down allowing corrosion to initiate. Figure 2-3 illustrates the effects of moisture, temperature, and salts on soil resistivity.



(a) Moisture (b) Temperature (c) Added Salt

Figure 2-3
Environmental effects on soil resistivity

Soil Classification

Soils are classified by their percentage content of sand, loam, and silt. Knowing the soil composition allows a corrosion engineer to understand how corrosive the environment may be. Table 2-4 shows the range of resistivities of several soil types.

Table 2-4
Examples of soil resistivities of various soil compositions

Medium	**Resistivity(Ω cm)**		
	Minimum	**Average**	**Maximum**
Surface soils, loam, etc	10^2		5×10^3
Clay	2×10^2		10^4
Sand and gravel	5×10^3		10^5
Surface limestone	10^4		10^6
Limestone	5×10^2		4×10^5
Shale	5×10^2		10^4
Granites, basalts, etc		10^6	
Decomposed gneisses	5×10^3		5×10^4
Slates, etc.	10^3		10^4
Fresh water lakes		2×10^4	2×10^7
Tap water	10^3		5×10^3
Sea water	20	10^2	2×10^2
Pastoral, low hills, rich soil, typical of Dallas, Texas; Lincoln, Nebraska Areas		3×10^3	
Flat country, marshy, densely wooded typical of Louisiana near Mississippi River	2×10^2	10^4	
Pastoral, medium hills and forestation, typical of Maryland, Pennsylvania, New York, exclusive of mountainous territory and seacoasts		2×10^4	
Rocky soil, steep hills, typical of New England	10^3	5×10^4	10^5
Sandy, dry, flat, typical of coastal country	10^3	5×10^4	5×10^5
City, industrial areas		10^5	10^6
Fills, ashes, cinders, brine, waste	6×10^2	2.5×10^3	7×10^3
Clay, shale, gumbo, loam	3×10^2	4×10^3	2×10^4
Same-with varying proportion of sand and gravel	10^3	1.5×10^4	10^5
Gravel, sand stones with little clay or loam, granite	5×10^4	10^5	10^6

Temperature Gradients

Geographic locations can be categorized by levels of thermal and moisture content. The locations are generally characterized by an average condition so that the resulting corrosion rates will be representative throughout the year. At the thermal extremes, the polar and tundra regions have cold climates while desert, grasslands, and deciduous forests in savannas, and tropical rain forests have hot climates. Humidity levels vary from desert to rain forest with polar, tundra, boreal forest, prairie, and savanna having average conditions.

Corrosion Rates and Modeling

Corrosion rates may be measured using electrochemical techniques and confirmed through gravimetry. Corrosion models may be constructed by measuring corrosion rates and applying weighting factors specific to each soil to those variables quantified in laboratory testing.

The corrosion rate of a structure site will indicate if the soils are currently oxidizing or reducing by the severity of the corrosion level. If the corrosion rate is ½ mil or less per year, we may consider the soil to be a reducing soil. Conversely, the corrosion rates can exceed those levels by a magnitude or more if there are strong depolarizers present in the soil or water.

Measurement of the redox level of the site will also provide some insight into the type of soil or condition of the soil at that point in time. Redox is an indication of the dissolved oxygen levels in the electrolyte; it is only useful to determine if there are reduction reactions taking place at the time of testing. This limitation is significant because many of the reactions that take place in the soil are reversible. For example, after a rainfall the soil becomes saturated and water replaces the oxygen in the pore spaces. Once this happens the soil becomes an oxidizing soil until the soil drains and oxygen once again fills the pore spaces in the soil. Soil moisture measurements should be made during testing to correlate the corrosion rates with the redox potentials.

Instantaneous corrosion testing can provide in situ corrosion rate measurements for the materials used in the construction of the structure at that particular site. Careful selection of pin materials can determine the corrosion rates for the galvanizing, copper grounds, and test coupons. Test coupons provide access to a structure or trend the influences of the environment around the structure.

Linear polarization testing can provide high production rates that are repeatable. The test method can be adapted to virtually any structure construction style such as lattice, anchors, or tubular structures.

3

CORROSION PROBE DEVELOPMENT

This chapter summarizes EPRI corrosion sensor R&D and describes the development of a corrosion probe sensor based on the linear polarization resistance technique. The chapter also describes a conceptual corrosion sensor and data acquisition system whose development is continuing in 2014 and beyond. Some of the material in this chapter is adapted from the 2012 technical update reports *Evaluation of New and Emerging Corrosion Sensors: Corrosion Model Development for Soils* (EPRI report 1024123) and *Corrosion Probe Development: Interim Report* (EPRI report 1024121).

Background

There are many sensor types that monitor environmental conditions or a change in state of a structure's construction materials. Some sensors monitor the failure of a protective coating while some trend changes in the environment that govern the severity of corrosion. Finally, some sensors will monitor specific kinetics of the corrosion process and interpret the effects in terms of corrosion rate. The EPRI research plan on ground grid corrosion focuses on the third type of sensors—those that use potential measurements to predict corrosion rates and mass loss.

Evaluation of Corrosion Sensors

To identify sensor types useful in monitoring corrosion in metal structures, the EPRI project team conducted a literature survey to identify what work has been completed to date on corrosion measuring systems. Researchers also quantify the effectiveness of sensors used in the EPRI corrosion laboratory in Charlotte, NC.

For the laboratory-testing phase of the project, the team selected two soils for exposure testing with a 1018 carbon steel coupon, a material that is representative of most lattice structures in service. They designed the soil exposure test so that soil temperature could be held at various set points and the resulting changes in environmental factors such as moisture content, REDOX, and coupon potential could be monitored over time. The team developed a corrosion rate model to allow mass loss from driving potentials and exposed surface areas measured in a laboratory experiment or by field surveys.

Based on this evaluation EPRI selected Linear Polarization Resistance (LPR) technology as the basis for a corrosion probe that can be used in the field to obtain a rapid estimate of the corrosion rate of a metal in soils of low resistivity. LPR testing has the potential to provide repeatable results on a large scale and the test method can be adapted to virtually any structure construction style such as lattice, anchors, or tubular structures.

Corrosion Rate Measurement

The corrosion rate of a structure site will indicate if the soils are currently oxidizing or reducing by the severity of the corrosion level. If the corrosion rate is ½ mil or less per year we may consider the soil to be a reducing soil. Conversely, the corrosion rates can exceed those levels by a magnitude or more if there are strong depolarizers present in the soil or water.

Measurement of the redox level of the site will also provide some insight into the type of soil or condition of the soil at that point in time. Redox is an indication of the dissolved oxygen levels in the electrolyte; it is only useful to determine if there are reduction reactions taking place at the time of testing. This limitation is significant because many of the reactions that take place in the soil are reversible. For example, after a rainfall the soil becomes saturated and water replaces the oxygen in the pore spaces. Once this happens the soil becomes an oxidizing soil until the soil drains and oxygen once again fills the pore spaces in the soil. Soil moisture measurements should be made during testing to correlate the corrosion rates with the redox potentials.

Instantaneous corrosion testing can provide *in situ* corrosion rate measurements for the materials used in the construction of the structure at that particular site. Careful selection of pin materials can determine the corrosion rates for the galvanizing, copper grounds, and test coupons. Test coupons provide access to a structure or trend the influences of the environment around the structure. Linear polarization testing can provide high production rates that are repeatable. The test method can be adapted to virtually any structure construction style such as lattice, anchors, or tubular structures.

Development of the LPR Corrosion Probe

The project team developed and implemented a four-phase testing program of an LPR probe. In the first phase, the team created a series of controlled laboratory environments to gather test data and confirm that the data were valid through complementary testing methods and modeling of the corrosion rates. In the second phase, they increased the scale of the testing to include larger test specimens and add limited environmental variability by installing test specimens at the Klondike (Southern Company Substation and Training Facility) test facility. In the third phase, the team installed terminal stations in order to limit or monitor environmental variability at the Klondike facility by making it possible to control the environment through irrigation and to collect data using instrumentation coupled to test coupons. In the fourth phase, they constructed a model to understand sources of error, develop an algorithm specific to a given site, and test the limits of the conformance values between results derived from LPR and gravimetric methods.

Results

A year of test data collection using two different potentiostats resulted in credible and relatively repeatable data that correlated with hand corrosion rate calculations. Laboratory exposure testing on more than one hundred soil samples provided both linear polarization resistance and gravimetric data for analysis—the gravimetric method, which relies on mass loss to quantify corrosion, serves to validate the results of the LPR probe. The test results for the development of a noninvasive, field method for corrosion measurements on a structure have shown promise. There is reasonable convergence between the mass loss method and the linear polarization technique, although the results do not correlate as well with the direct assessment measurements from field surveys. More experimentation and modeling are needed to define the effects of environmental conditions on corrosion rates.

4

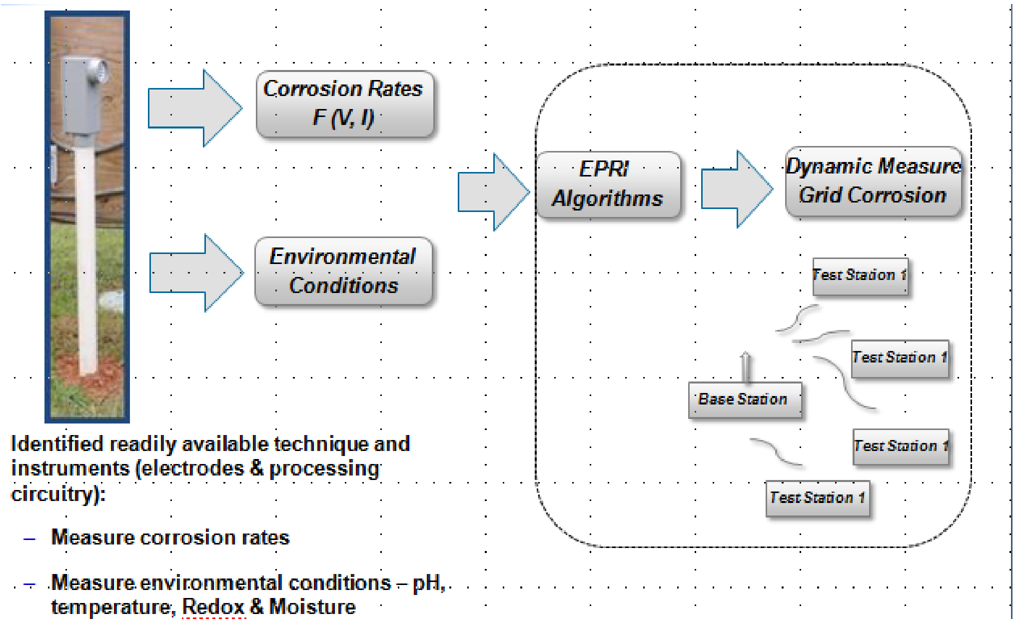
FURTHER DEVELOPMENT: R&D ACTION PLAN

This chapter describes work to be performed in 2014 and beyond in developing a field-deployable ground grid corrosion sensing and data acquisition system.

The preceding chapters of this report describe EPRI's ground grid corrosion R&D through 2013. To recap: EPRI researchers identified a readily available technique, linear polarization resistance, and developed the electrodes and processing circuitry to measure subgrade corrosion rates and the environmental conditions (temperature, moisture, pH and redox) that influence corrosion rates. EPRI algorithms derived through lab testing have conformed to corrosion rates.

This work was the first phase in developing a population assessment method for fleet management. The sensor system will dynamically measure ground grid corrosion via LPR probes. Probe data will be transmitted via cellular uplinks to a base station where it will be compiled and made available for analysis.

Figure 4-1 shows the envisioned system. The work performed through 2013 is represented in the left side of the figure. The right side of the figure shows the work to be performed in 2014 and beyond to develop and test the sensor system.



Identified readily available technique and instruments (electrodes & processing circuitry):

- Measure corrosion rates
- Measure environmental conditions – pH, temperature, Redox & Moisture

Figure 4-1
EPRI Corrosion Sensor Array

Next Steps

In the project's next phase, extending through 2014, the project team will:

- Model soil and environmental data. Researchers will collect soil samples from multiple substation sites for analysis in EPRI's Charlotte laboratory. They will also obtain GPS coordinates of substation test sites for correlation with government geographical information system (GIS) environmental data.
- Develop algorithms. Additional soil and environmental data will support refinement of the algorithms that will take multiple layers of data—soil data from the field including moisture and pH, probe data including ground grid potentials, and environmental data—and calculate site-specific corrosion rates.
- Continue hardware development. The project team will continue to refine the sensor and data acquisition and analysis system.

The project's next major phase will expand the system's capabilities beyond subgrade corrosion to atmospheric corrosion of components including transformer and circuit breaker tanks and specific materials of construction such as zinc, carbon steel, concrete, and coating systems.

The project team will then demonstrate the system for fleet management applications including condition assessment, optimized inspection cycles, and service life predictions to support cost-effective maintenance and replacement decisions.

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